

# **Computational Study of Water Mitigation Effects On An Explosion Inside A Vented Tunnel System**

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## **ABSTRACT**

The effects of water in close contact with detonating high explosives have been studied experimentally by numerous researchers, such as Eriksson (1974), Keenan & Wager (1992) and etc. These tests series had demonstrated that when water was stored closed to the high explosives, both the maximum overpressure and impulse density could be reduced significantly. This reduction has been attributed to the loss of energy from the shock into breaking up the water into droplets and the process of phase change of water from liquid to gas due to shock vaporization which subsequently, reduces the surrounding temperature. The purpose of the present work is to study computationally the mitigation effects of water to an explosion inside a tunnel system with venting. A series of three-dimensional numerical calculations using a Multimaterial Eulerian Finite Element code, MSC-Dytran, has been conducted. In order to capture the behavior of water subjected to shock loading, appropriate equation of state for water has to be determined. This is based on experimental data for shock Hugoniot for water and the Mie-Gruneisen equation of state for water has been chosen. Results from the present study show that water is capable of reducing the peak pressure due to an explosion and the configuration of water surrounding the explosive is important for water mitigation to be effective.

## **INTRODUCTION**

The effects of water in close contact with detonating high explosives have been studied by Eriksson (1974), Keenan & Wager (1992), Vretblad & Eriksson (1994) and etc. These test series had demonstrated that when water were stored closed to the high explosives, both the maximum overpressure and impulse density could be reduced significantly. This is due to the energy loss from the shock to breaking up the water into small drops, increasing surface area for heat transfer for vaporization and subsequently, reduces the temperature of the surrounding as the water is vaporized.

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Hence, this water concept offers the potential for major savings in the cost for explosives safety of ordnance facilities from accidental explosions and for survivability of combat facilities from enemy weapons. It is therefore of interest to us to show computationally if water is effective to mitigating the pressures due to an explosion and to study the effect of water configurations on the shock pressure.

## NUMERICAL MODELING

Figure 1 shows the layout of the tunnel in Alvdaalen. The dimensions of the larger chamber is 4 m wide, 3 m high and 25 m long with arched roof. A 75 m long tunnel, 2.5 m wide and 2.5 m high, leads directly from the front of the chamber to a portal. All boundaries are assumed to be rigid. This simplification allows faster preparation of the model and also reduces the computational time greatly.

1000 kg of TNT are placed in the center of the chamber and pressure signatures are measured at several locations, as shown in Table I. The explosive charge is modeled as cylindrical charge (C) of radius 0.33 m and length of 1.8 m, see Figure 2. Figure 2 also shows the layout of the water (W) surrounding the explosive (water configuration 1).

Air-blast calculation is performed without water for the explosive and detonation starts from the center of the explosives. Numerical calculations are performed with three different water configurations. They are water configuration 1, consisting of four block of waters surrounding the explosive (see Figure 2), water configuration 2 (see Figure 3), and water configuration 3 which consists of a water wall located just in front of the chamber's exit, leading to the small tunnel. The water wall is located at 11 m away from the center of the explosives with thickness of 0.32 m, height of 2.4 m and width of 2.6 m. In these calculations, water to charge weight ratio used is 2. This gives the weight of water of 2000 kg. Besides this, additional calculations are carried out with water configuration 1 by reducing the air gap distance by 0.8 m between the water blocks and the explosive, and varying the water to charge weight ratio from 3 to 4 for water configuration 2.

In the present study, three-dimensional calculations were performed with hexahedron elements. An outflow boundary condition is implemented at the tunnel exit. Material modeling of the explosive and water uses the equation of state model to characterize the behavior of the detonation product and water subjected to high loading.

Development of the detonation product gases is modeled with the standard Jones-Wilkins-Lee (JWL) equation of state (EOS). The equation of pressure  $P$  is given as

$$P = A \left( 1 - \frac{\omega}{R_1 V} \right) e^{-R_1 V} + B \left( 1 - \frac{\omega}{R_2 V} \right) e^{-R_2 V} + \frac{\omega E}{V} \quad (1)$$

where  $A$ ,  $B$ ,  $\omega$ ,  $R_1$ ,  $R_2$  are constants,  $V$  is the specific volume of detonation products over the specific volume of undetonated explosive and  $E$  is the internal energy per unit volume. The density of TNT is 1630 kg/m<sup>3</sup>. The values used for JWL TNT were

obtained from the handbook by Dobratz (1981). Air is modeled as an ideal gas which uses a gamma law equation of state:

$$P = (\gamma - 1) \frac{\rho}{\rho_o} E \quad (2)$$

where,  $\gamma = 1.4$  is the ratio of specific heats. The initial density of air,  $\rho_o$ , is  $1 \text{ kg} / \text{m}^3$ . The initial internal energy,  $E$ , is 2.5 bar in order to satisfy standard atmosphere pressure.

Water is modeled as a compressible fluid with a Mie-Gruneisen equation of state which uses cubic shock velocity-particle velocity to define pressure for compressed and expanded materials as,

In compression ( $\mu > 0$ )

$$P = \rho_o C_o^2 \mu \left[ 1 + \left( 1 - \frac{\gamma_o}{2} \right) \mu - \frac{a}{2} \mu^2 \right] \times \left[ 1 - (S_1 - 1) \mu - S_2 \frac{\mu^2}{1 + \mu} - S_3 \frac{\mu^3}{(1 + \mu)^2} \right]^{-2} + (\gamma_o + a\mu)E \quad (3)$$

In tension ( $\mu < 0$ )

$$P = \rho_o C_o^2 \mu + (\gamma_o + a\mu)E \quad (4)$$

where,

$$\mu = \eta - 1 = (\rho - \rho_o) / \rho_o.$$

$\gamma_o$  is the Gruneisen gamma,  $a$  is the first order volume correction to  $\gamma_o$ ,  $\rho_o$  is the density of water,  $E$  is the specific internal energy,  $C_o$  is the sound speed at undisturbed state and  $S_1$ ,  $S_2$  and  $S_3$  are constants.

The above equation of state for water can be expressed in polynomial form (Shin et al, 1998) as;

In compression ( $\mu > 0$ )

$$P = a_1 \mu + a_2 \mu^2 + a_3 \mu^3 + (b_0 + b_1 \mu + b_2 \mu^2) \rho_o E \quad (5)$$

In tension ( $\mu < 0$ )

$$P = a_1 \mu + (b_0 + b_1 \mu) \rho_o E \quad (6)$$

where,

$$a_1, a_2, a_3, b_0, b_1, b_2 \text{ are constants for the water.}$$

Constants for these equations were determined based on the Mie-Gruneisen EOS (Steinberg, 1987). Hence, the above equation of state for water can be used over the range for which the Mie-Gruneisen EOS is valid. This covers the pressure range from

0 to 40 GPa and temperature range from 20 °C to 2777 °C. The above polynomial form of equation of state for water (Shin et al, 1998) is implemented in the present analysis.

## RESULTS AND DISCUSSIONS

The Multimaterial Eulerian Finite Element code MSC-DYTRAN version 3.0 (MSC/DYTRAN User's Manual, 1996) was applied to model the current problem including the explosion event, water-shock and blast waves propagation and reflection at the water-air interface. This code is supported by the MacNeal-Schwendler Corporation. Multimaterial Eulerian processor in this code allows up to nine different Eulerian materials to be present in a given problem. The finite element model for the MSC-DYTRAN can use either the MSC-XL or MSC-PATRAN as pre-processor and post-processor.

## NUMERICAL VERIFICATION

In this section, numerical results are first compared with experimental data of Joachim & Lundermann (1993).

To verify the numerical procedure, a comparison with experimental data provided by Joachim & Lundermann (1993) was conducted. The model used in the experiments of Joachim & Lundermann (1993), consisted of a detonation chamber and an exit tunnel. The detonation chamber was made of a 0.508 m (inside diameter) steel pipe and rings of steel plate (0.076 m thick) and had an outer diameter of 0.813 m. The detonation chamber was 1.8 m long with a volume of 0.365 m<sup>3</sup>. The exit tunnel was made of heavy-walled steel pipe with an inside diameter of 0.146 m and had a total length of 4 m. In our numerical modeling, the boundaries are assumed to be rigid and this reduces the computational domain, thus increasing the speed of computation.

Explosive charges for the numerical calculations are made of Composition C-4, as in the experiment and are modeled as cylindrical charges with equal height and diameter. The charges are placed at the center of the chamber and detonation is initiated at the one end of the cylindrical charge which is closest to the exit tunnel. The water is also modeled in cylindrical shape with equal height and diameter as the charge and the explosive is fully immersed in the water. Numerical calculations were performed for explosive detonated in air tunnel for loading density of 5.00 kg/m<sup>3</sup> (charge weight of 1.36 kg) and with water to charge weight ratio of 1.3, 2.0 and 3.3.

Figure 4 shows the comparison between experiment and computation for 1.36 kg (loading density of 5.00 kg/m<sup>3</sup>) C-4 charge detonation in air tunnel. The triangles denote experimental data and the circles are computed results from our simulation. This notation applies throughout the figures unless stated otherwise. The figure shows peak pressure plotted against distance of pressure point from the rear of chamber in log scale. We can see that the simulation's results are in very good agreement with the experimental data.

Figures 5 to 7 show the comparison between experiment and computation for 1.36 kg (loading density of 5.0 kg/m<sup>3</sup>) C-4 charge detonation with water-explosive ratio of 1.3, 2.0 and 3.3. In these figures, the numerical results are in very good agreement with the experiment. In general, our peak pressure calculations show good

agreement with the experiment for the case of explosive with water and this gives the confidence in our numerical simulations.

#### ***A. Varying Water-Charge Weight Ratio***

In this section, the effects of water to charge weight ratio on the explosion induced shock pressure are studied.

Figures 8 to 10 show the pressure time history curves at different locations generated from the explosion of a cylindrical charge detonated from the center of the explosives. The pressure time history curves of explosion in air, without water are denoted by solid grey lines. Water configuration 2 is used (see Figure 3), with water to charge weight ratio of 2 (denoted by solid lines), 3 (denoted by light dashed lines) and 4 (denoted by dark dashed lines). It can be seen from the figures that water is effective to mitigate the maximum peak pressure and impulse density due to an explosion. Shock arrival time is also delayed with the presence of water. As the water to charge weight ratio is increased from 2 to 4, the reduction in maximum peak pressure also increases. However, the amount of reduction in maximum peak pressure from water-charge weight ratio of 3 to 4 is not significant. This shows that there is an upper limit to the amount of water that can be used after which there is no further reduction of maximum peak pressure.

#### ***B. Varying Distance Between Water Blocks And Explosive With Fixed Water-Charge Weight Ratio***

Figure 11 to 13 show the pressure time history curves at different locations for the case of water configuration 1 with different distances between the water blocks and the explosive. In these calculations, water to charge weight ratio is maintained at 2. Solid lines denote the explosion in air, without water. The dark short dashed lines denote for the case of water blocks with locations as shown in Figure 2. The light short dashed lines denote for the case of water blocks being located closer to the explosive by 0.8 m as compared to Figure 2.

It can be seen from these figures that there is reduction in the maximum peak pressure for both cases with water. For water configuration 2 with the placement of water blocks as shown in Figure 2, the reduction in maximum peak pressure is not significant. However, when the water blocks are placed nearer to the explosives with the same water-charge weight ratio, there is an increase in the maximum peak pressure reduction. Shock arrival time for the maximum peak pressure is slightly delayed for both cases with water. However, the delay in shock arrival time for the second peak is more obvious for the case of water blocks placed nearer to the explosives. These calculations demonstrate that for water mitigation to be effective, there is a need for the water to be in contact with the shock wave at early stage.

#### ***C. Varying Water Configuration With Fixed Water-Charge Weight Ratio***

The next three figures (Figures 14 to 16) show the pressure time history curve for cases of different water configurations used in the numerical calculations with fixed water-charge weight ratio maintained at 2. Solid lines denote the case without water. Dark short dashed lines denote the case of water configuration 2. Light short dashed

lines denote the case of water configuration 1 with water blocks placed at locations as shown in Figure 2. Finally, the grey solid lines denote the case of water wall placed near the chamber's exit with thickness of 0.32 m, height of 2.4 m and width of 2.6 m.

It can be seen from the figures that water configuration 2 in which the explosives are fully immersed with water, yields the most reduction in the maximum peak pressure and shock arrival time is also significantly delayed as compared to the rests. These results demonstrated the importance to have the water as close to the explosive as possible in order to achieve better mitigation effects.

Finally, Figure 17 shows the plot of maximum peak pressure versus distance from the explosives in log scale for different water configurations. Triangles denote the case without water, diamonds denote the case of water configuration 1 with water blocks' locations as shown in Figure 2 and circles denote the case of water configuration 2. For both cases with water, the ratio of water to charge weight ratio is fixed at 2. The figure shows that there exists a relation between the maximum peak pressure and the distance from the explosives. The maximum peak pressure decreases with increase in the distance from the explosives. Such relation has also been observed by Joachim & Lundermann (1993) in their experiments.

## CONCLUSION

The present study demonstrates that the numerical simulations are in good agreement with the experiments of Joachim & Lundermann (1993) for explosion with and without water. The results from our simulations prove the experimental findings of the potential and effectiveness of water in reducing peak pressures from an explosion. Significant peak pressure reduction can be achieved with increase in the water-explosive ratio. However, there is an upper limit to the amount of water that can be used. It is also shown that the configuration of water is important for mitigation to be effective.

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Table I. Locations of the pressure points.

Pressure Points	X (m)	Y (m)	Z(m)
A1	18.75	3.0	0.0
A2	37.5	0.0	0.0
A3	75.0	0.0	0.0

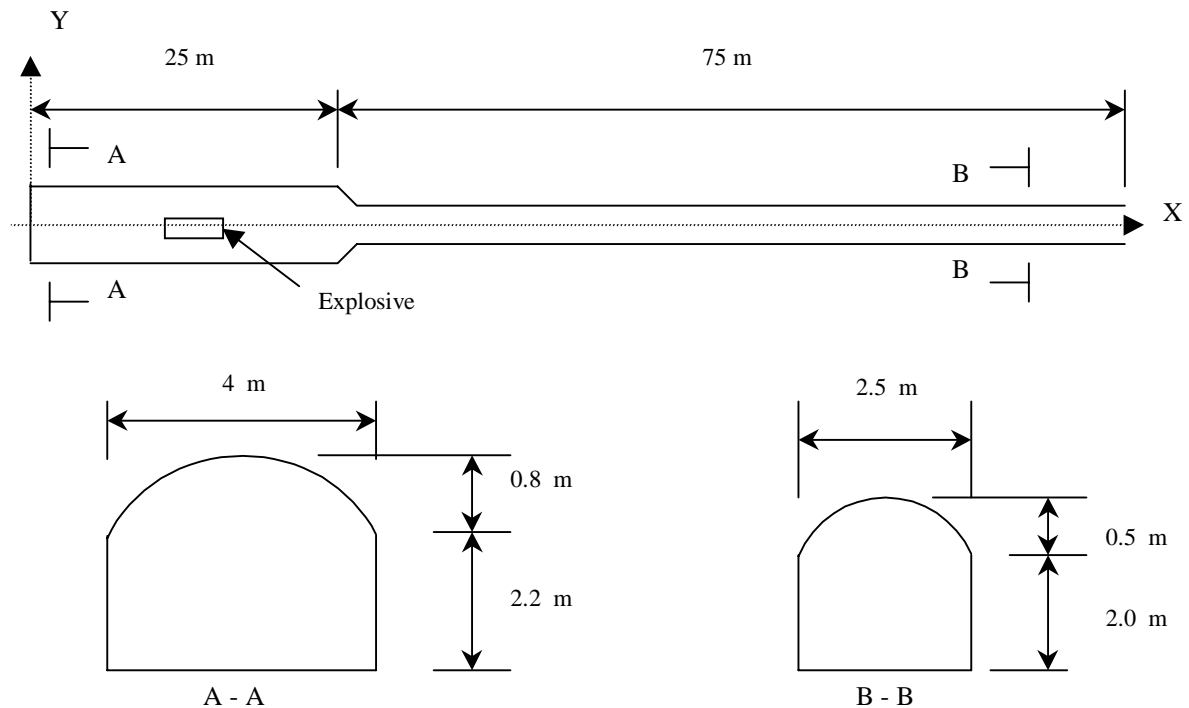


Figure 1. Layout of the tunnel.

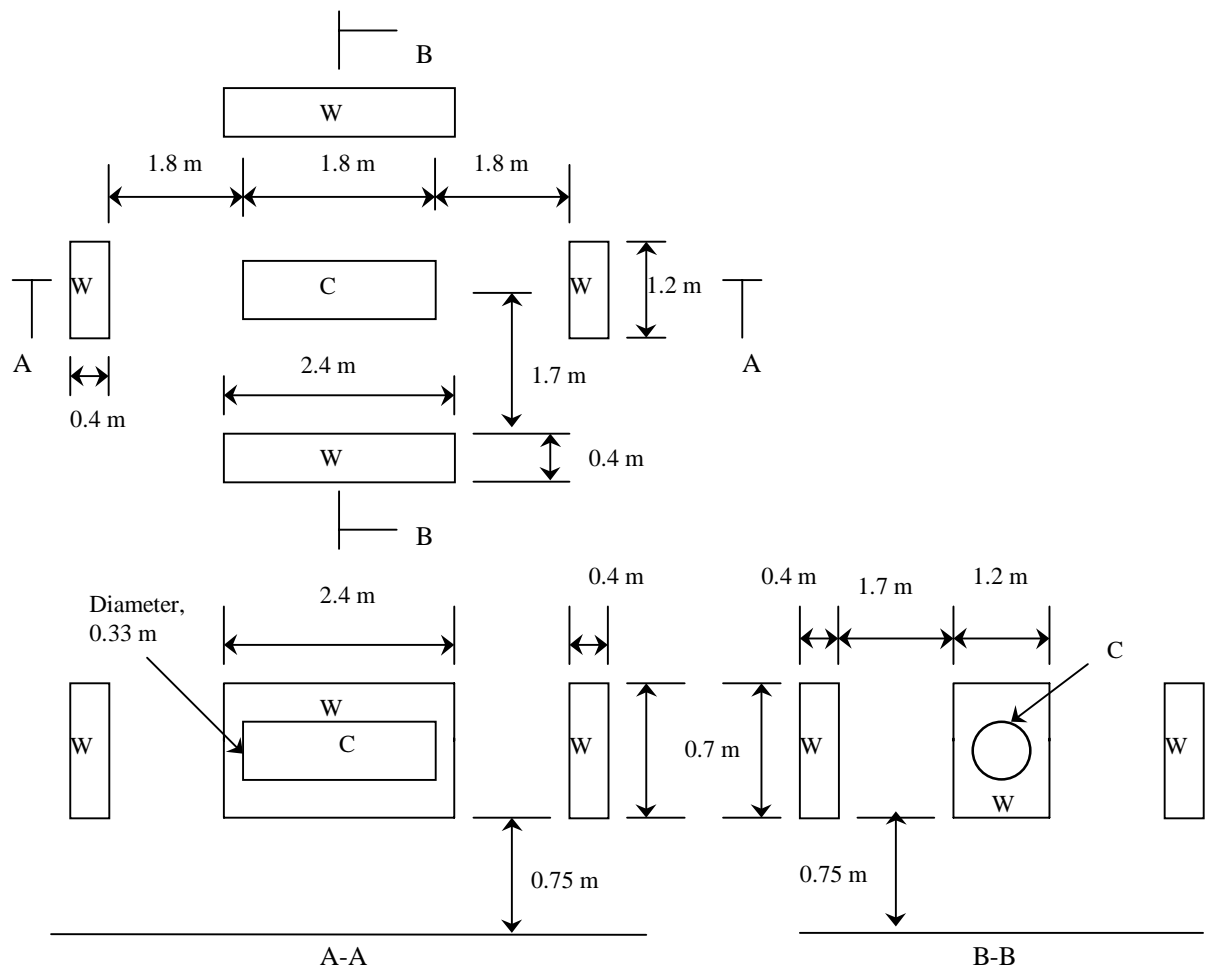


Figure 2. Layout of water configuration 1 and the explosive charge.

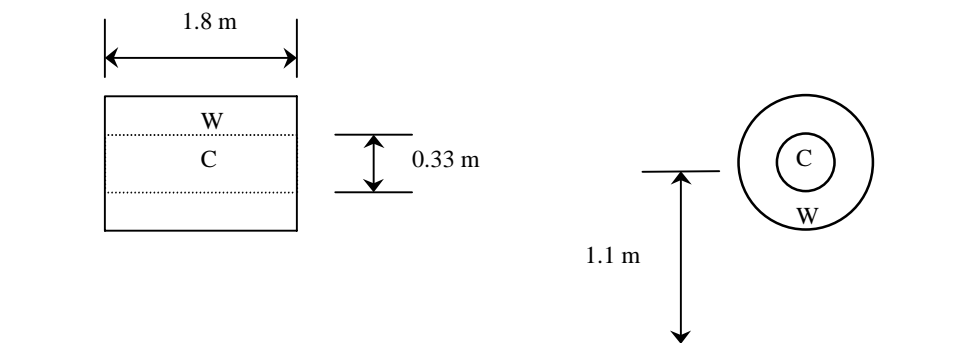


Figure 3. Layout of water configuration 2.

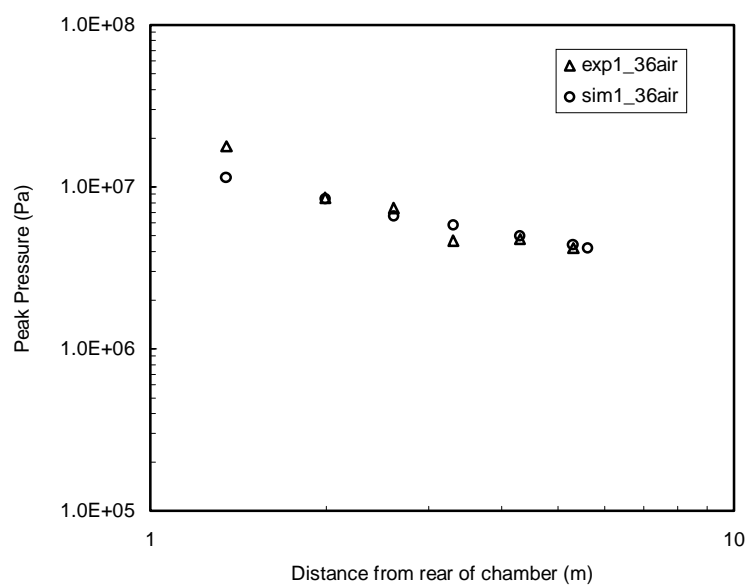


Figure 4. Comparison between experiment and computation for 1.36 kg C4 charge detonation in air.

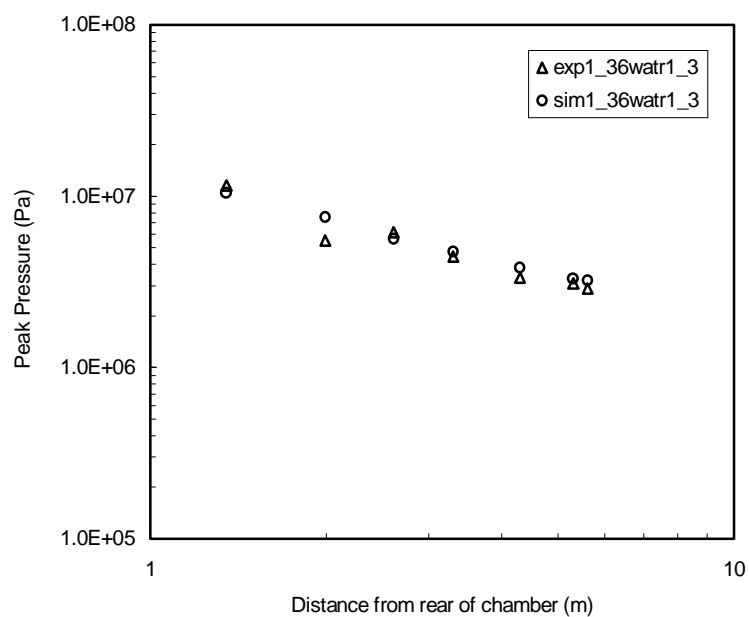


Figure 5. Comparison between experiment and computation for 1.36 kg C4 charge detonation with water ( $R=1.3$ ).

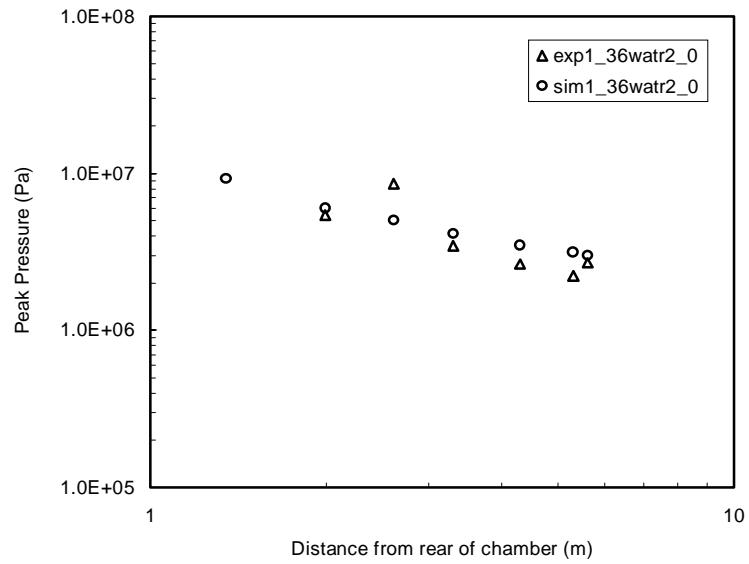


Figure 6. Comparison between experiment and computation for 1.36 kg C4 charge detonation with water ( $R=2.0$ ).

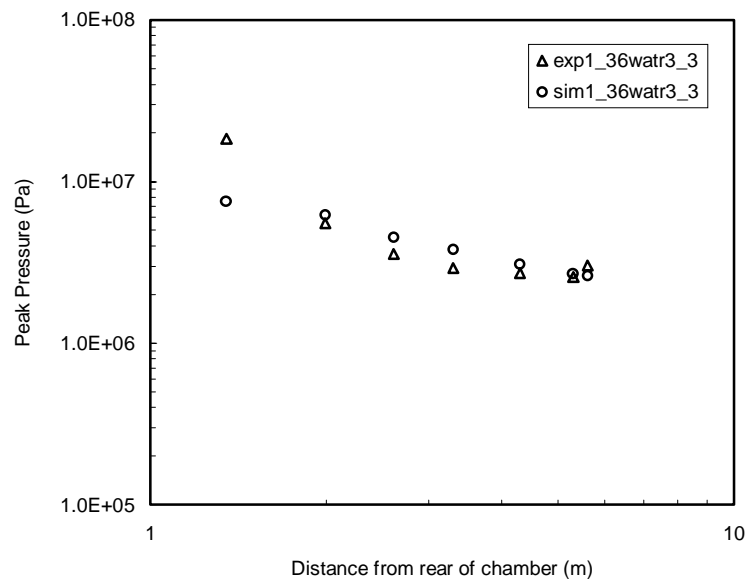


Figure 7. Comparison between experiment and computation for 1.36 kg C4 charge detonation with water ( $R=3.3$ ).

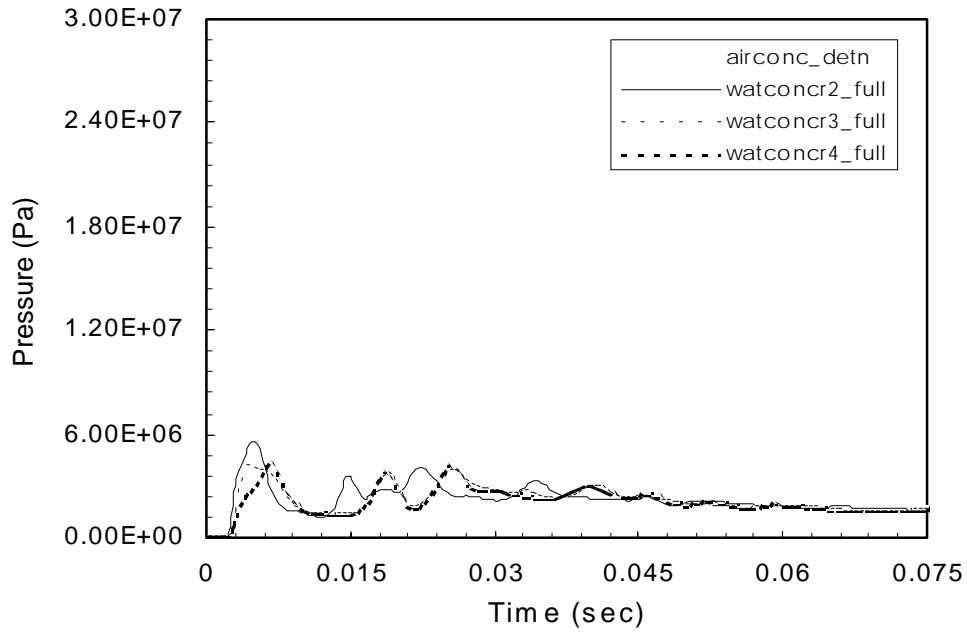


Figure 8. Pressure signatures at A1 of an explosion in a tunnel.

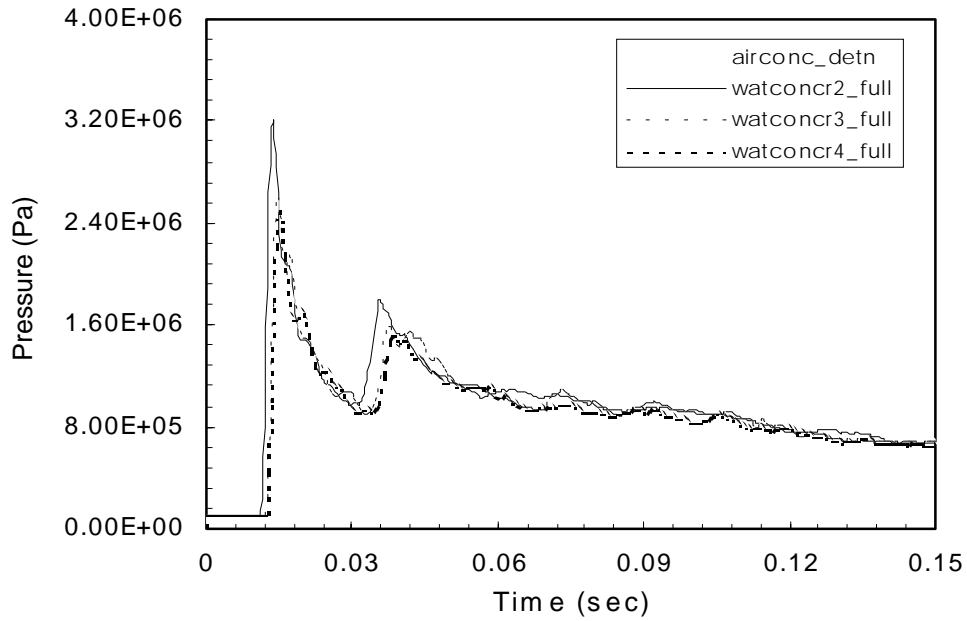


Figure 9. Pressure signatures at A2 of an explosion in a tunnel.

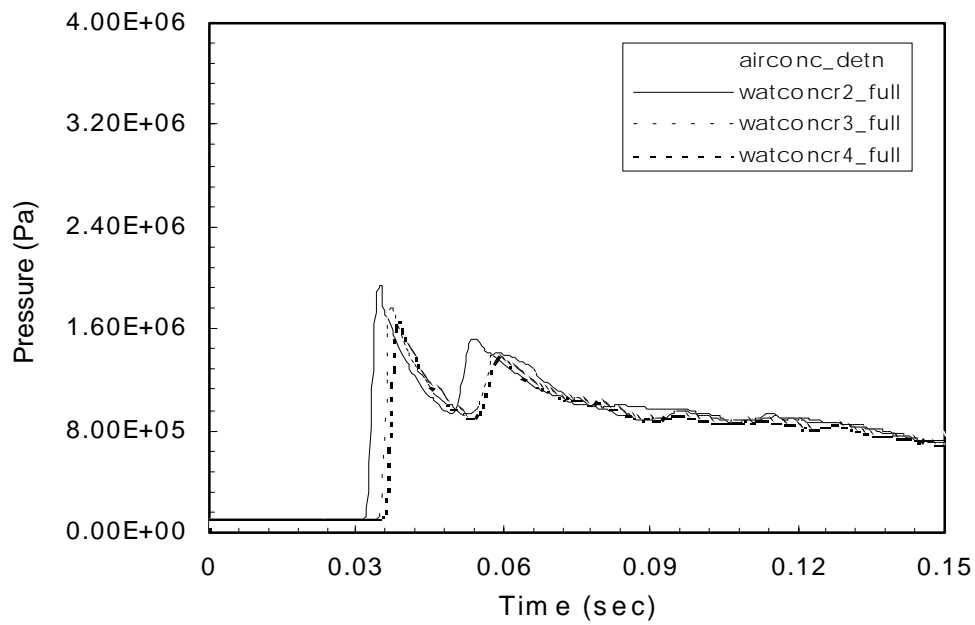


Figure 10. Pressure signatures at A3 of an explosion in a tunnel.

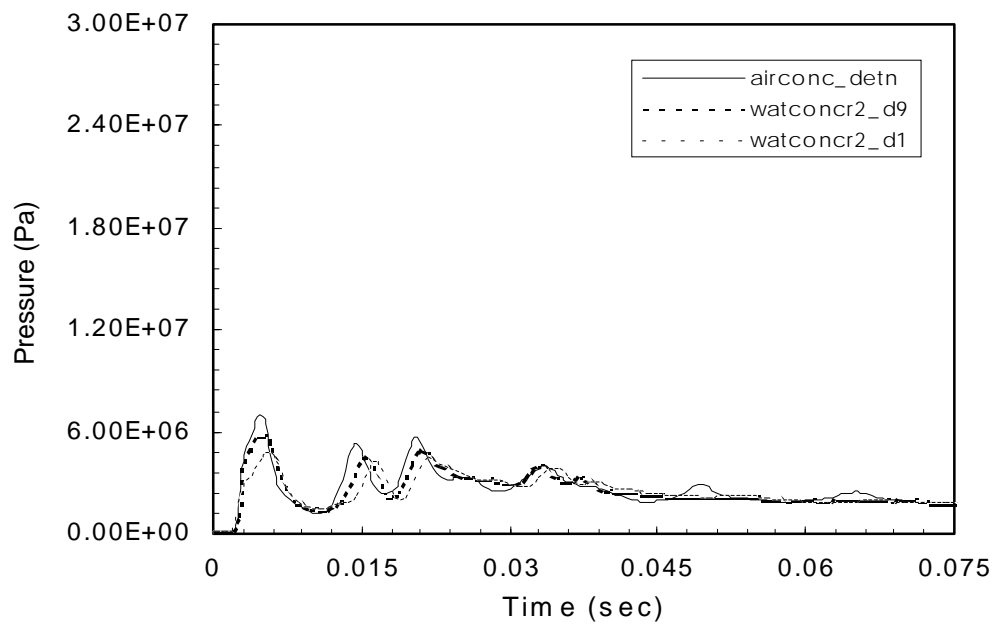


Figure 11. Pressure signatures at A1 of an explosion in a tunnel.

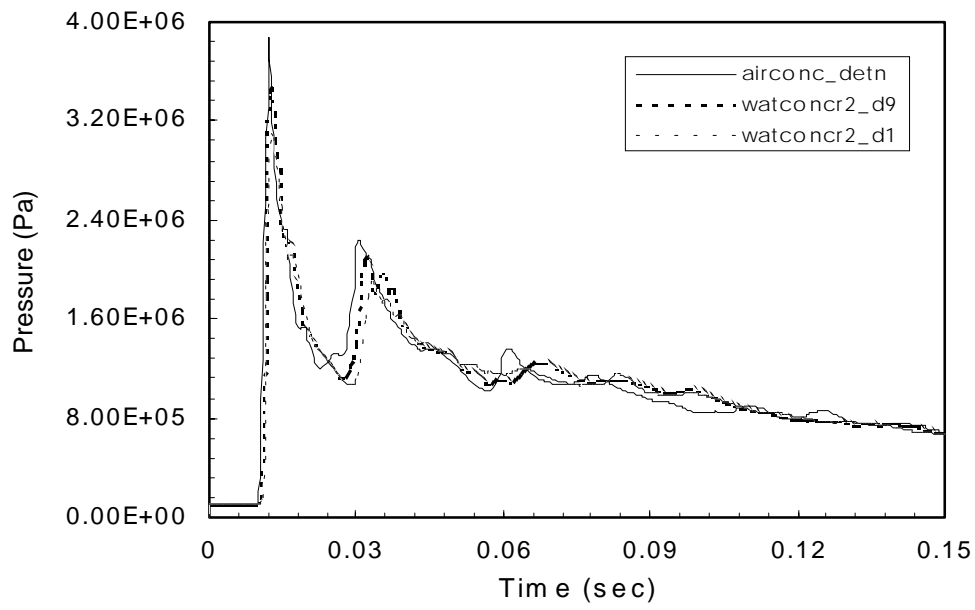


Figure 12. Pressure signatures at A2 of an explosion in a tunnel.

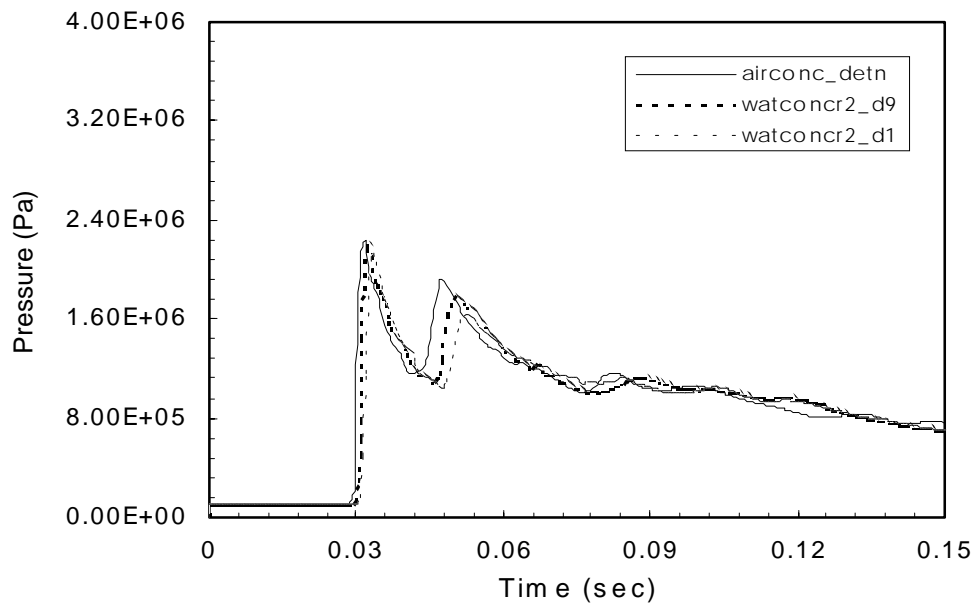


Figure 13. Pressure signatures at A3 of an explosion in a tunnel.

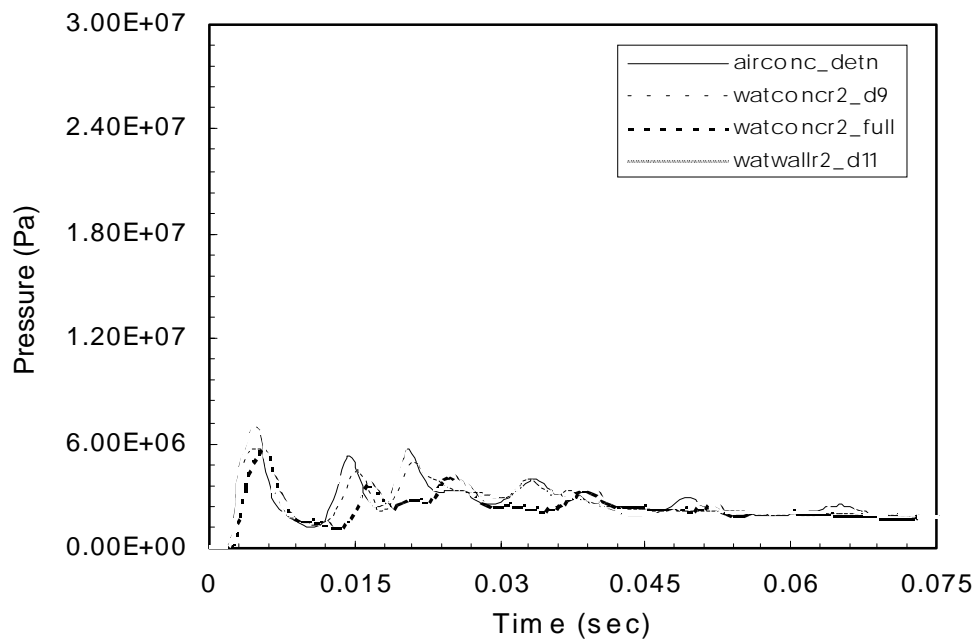


Figure 14. Pressure signatures at A1 of an explosion in a tunnel.

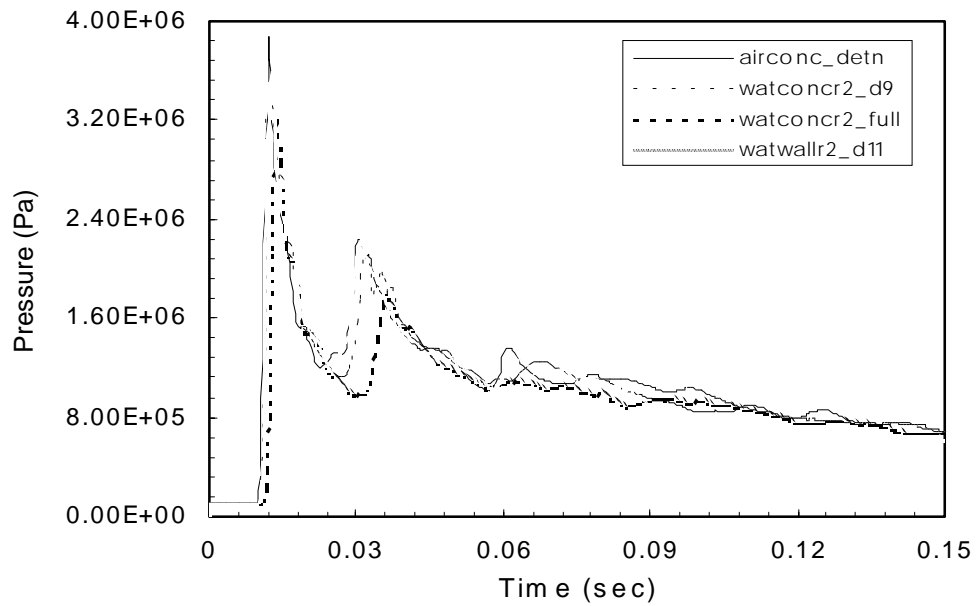


Figure 15. Pressure signatures at A2 of an explosion in a tunnel.

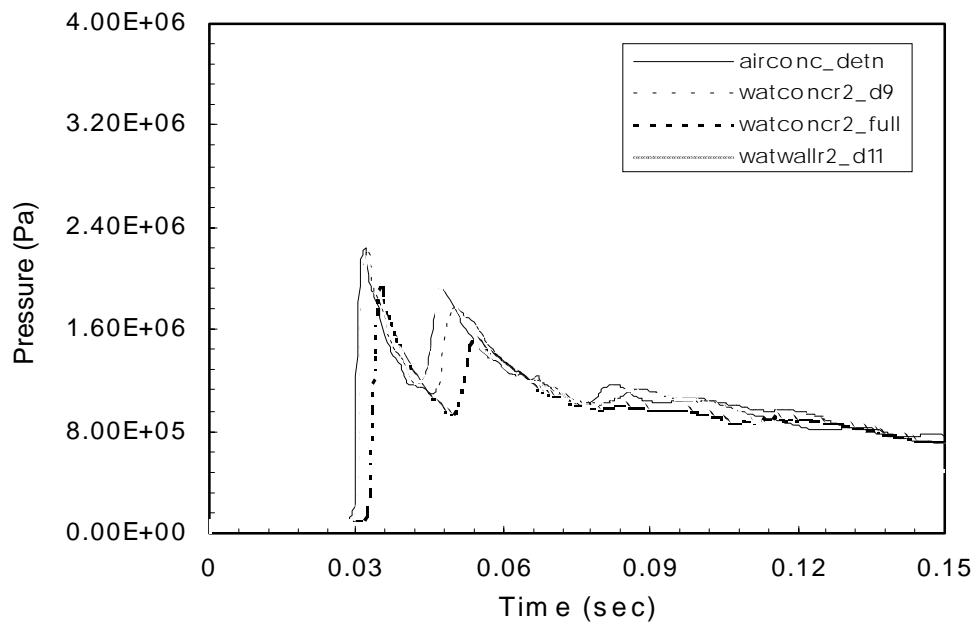


Figure 16. Pressure signatures at A3 of an explosion in a tunnel.

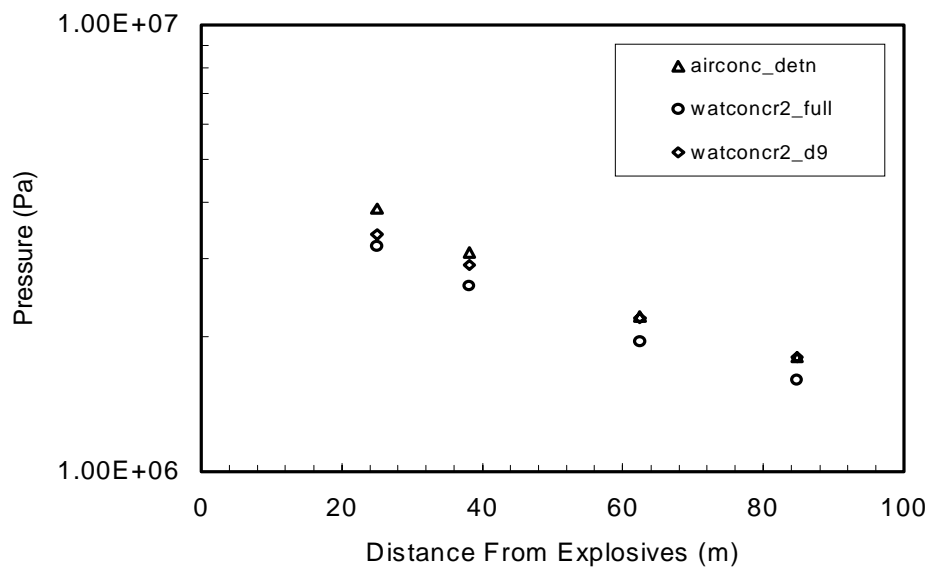


Figure 17. Maximum peak pressure versus distance from explosives.